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IMPLICATIONS OF OBJECT VS. SPACE BASED THEORIES OF ATTENTION IN THE DESIGN OF THE AIRCRAFT HEAD-UP DISPLAY

BY

JEFFRY LONG

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Submitted in partial fulfillment of the requirements for the degree of Master of Science in Psychology in the Graduate College of the University of Illinois at Urbana-Champaign, 1994

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IMPLICATIONS OF OBJECT VS. SPACE BASED THEORIES OF ATTENTION IN THE DESIGN OF THE AIRCRAFT HEAD-UP DISPLAY

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University of Illinois at Urbana-Champaign, 1993
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Thirty-two pilots flew instrument approaches in a high-fidelity simulator. Location of flight symbology was manipulated head-up vs. head-down while controlling for optical distance and symbology format. Pilots were assigned to one of two symbology sets, conformal or non-conformal. Each pilot flew half of the trials with the symbology presented in a head-up location and half with the symbology located head-down. An unexpected far domain event was presented on one trial per pilot. The results revealed that, for flight path control, there was generally a cost associated with head-down location. The magnitude of this cost was larger for conformal than for non-conformal symbology. Head-up presentation resulted in faster transition from instrument to visual flight reference, but slower response to the far domain unexpected event and greater error tracking digital airspeed. The results are interpreted with the theoretical framework of object-based and space-based theories of visual attention.

Acknowledgements

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Introduction

Since their inception shortly after World War II, Head-Up Displays (HUDs) have proliferated and can now be found in a wide range of aircraft, both military and civilian. A HUD consists of a Cathode Ray Tube (CRT) and a glass plate called a combiner. The pilot looks through the combiner to see the world in front of the aircraft. The HUD is constructed such that the pilot also sees an image of the CRT which is reflected off the combiner.

Evidence that HUDs better support overall flying performance than the Head-Down Instrument Panels (HDIPs) which preceded them is abundant (Fischer, Haines & Price, 1980; Greene, 1988; Hughes, Hassoun, and Barnaba, 1992; Steenblik, 1989; Wickens, Martin-Emerson, & Larish, 1993). The mechanisms underlying this performance enhancement are, however, far from fully understood. Part of the problem is that most comparisons between HUDs and HDIPs have been confounded by two variables: format and optical distance. The first confound results from the fact that most HUDs present information in a modern, computer-generated, highly integrated format whereas the head-down displays to which HUDs have typically been compared present information via conventional "round dials and gauges" instruments, some of which have remained essentially unchanged since the 1920's. The second confound arises because collimating HUD optics make the light rays coming from the display parallel and thereby deceive the eye into thinking that the image is located at or near optical infinity, whereas the HDIPs usually matched against HUDs are viewed at distances of about one meter. As a result, subjects in most experiments have had to change their eyes' focus in scanning between the outside scene and the head-down display, but not between the outside scene and the HUD. The literature contains compelling evidence that such reaccomodation can substantially impede performance (Fischer, Haines, & Price, 1984). As a result of these two confounds, it is unclear whether the findings of general HUD superiority should be attributed to the superimposed location of the HUD symbology or rather to its far optical distance and modern format. Some researchers have suggested that moving the HUD symbology to a head-down location and retaining its collimation might yield the same performance advantage over a conventional HDIP, while avoiding some of the "clutter" problems which could result from the superimposition of HUD symbology on the outside visual scene (Weintraub & Ensing, 1992). In order to determine the advisability of such an action, it is necessary to understand the

mechanisms by which the format of displayed information affects flight performance. A review of the relevant literature yields four categories of particular interest: object-based attention theories, space-based attention theories, ecological psychology, and cognitive capture.

Object-based attention theories

The first category is the literature dealing with object-based theories of attention. According to such theories, in the first stage of perception the visual scene is partitioned into separate objects based on Gestalt properties such as continuity of contour, common color, common shape, and common motion patterns, and in the second stage each object is analyzed in detail (Kahneman, 1973; Neisser, 1967). Once attention has been focused on an object, all attributes of that object are unavoidably processed. Whereas different objects are processed in series, the various attributes of a single object are processed in parallel (Kahneman & Triesman, 1984; Kramer, et al., 1985; Kramer & Jacobsen, 1991). A particularly noteworthy finding of object-based attention research is that two attributes on a single object are processed more rapidly when they are located on the same object than when they are distributed across different objects (Duncan, 1984).

Before applying this approach in the context of HUD symbology, it is necessary to draw a distinction between two symbology types, conformal and non-conformal. Conformal symbology is that which has a spatial analog in the far domain. When the outside scene is in view, the conformal symbology and its far domain analog move rigidly together. Further, if the conformal symbology is presented in a superimposed (head-up) format, the symbology will overlay its far domain analog, so that the two will share common contours. An example of such symbology can be found in the HUD described by Bray (1980), who proposed a virtual runway symbol which would mimic the shape and spatial location of the real runway. Non-conformal symbology, on the other hand, has no spatial analog in the far domain. An example of such symbology is an airspeed readout.

Returning to the predictions of object-based theories of attention, let us apply them to the example of a pilot flying an approach with a Bray HUD through bad weather. During the first part of the approach, the pilot will be attending exclusively to the perceptual group or object containing HUD information. As the aircraft approaches decision height and expected break-out

of the weather, the pilot begins to cross-check the outside scene in an effort to visually acquire the runway. The virtual runway symbol of the Bray HUD will overlay the real runway, and the two will move together and share a common shape. As a result, when the outside scene begins to come into view, the runway (target) element of the scene should be incorporated into the HUD perceptual group, while such remaining elements of the outside scene as roads and parking lots (distractor elements) should not. In the words of Simon (1991), "a single target is easier to detect among distractors if it is not part of a perceptual group to which the distractors belong" (p. 20). Object-based attention theories, therefore, seem to support the contention that a conformal symbology element will assist detection of the far domain element it represents to a greater degree if that symbology is superimposed (head-up) than if it is not (head-down).

Now let us apply object-based theories of attention to non-conformal HUD symbology. Non-conformal symbology lacks the advantage of overlaying and moving in unison with far domain elements. For this reason, such symbology, whether separated or superimposed, should not be part of any far-domain perceptual group. Object-based theories, therefore, seem to make no recommendations as to whether a purely non-conformal symbology set should be presented head-up or head-down.

Space-based attention theories

In the second category falls the work of researchers who have modeled attention as a function of spatial location. This approach has described attention with such metaphors as zoom-lenses, spotlights and gradients. These analogies illustrate the belief of the theorists who use them that visual attention is distributed across a contiguous area of visual space, the size of which can be adjusted (Eriksen & Eriksen, 1974; Eriksen & St. James, 1986; Eriksen & Yeh, 1985; Laberge & Brown, 1989; Wachtel, 1967). These and other researchers have observed that response to a target stimulus is hampered by the presence of a distractor stimulus within one degree of visual angle. Similar effects are also evident in more applied studies. In one such study, Schons (1993) examined the effects of physical separation of information sources in the context of the aircraft cockpit. They found that the presence of task-irrelevant information sources in close spatial proximity to task-relevant sources resulted in a performance decrement, or "clutter" penalty.

Another aviation study with implications for space-based theories was carried out by McCann, Foyle, and Johnston (1993). This study went beyond investigating mere adjacency of information sources in that it examined what happens when the contours of the two stimuli actually overlap. Subjects in this experiment flew a low-level flight simulation which required them to follow a path in the outside world. HUD altitude information was presented at varying levels of spatial separation. The researchers found that path-following performance for the most central HUD location was inferior to that in the conditions where the HUD and path information were more widely separated.

These findings are clearly relevant to the HUD since HUD superimposition places elements of the near and far domains close together in space and / or on top of one another. These studies therefore lead us to expect that when attention is focused on a HUD element, nearby far domain elements will act as distractors, exacting a toll on performance. Similarly, focused attention on elements of the far domain should be hindered by the presence of nearby HUD elements. It is important to qualify this expectation, however, in light of a 1991 study by Kramer and Jacobsen. These researchers manipulated both spatial proximity of stimuli and the imbedding of those stimuli into perceptual objects. One finding was that the performance-degrading effect of a distractor stimulus was nullified when that distractor was part of a different perceptual object than was the target stimulus. This finding held even when the distractor and target were separated by a mere 0.25 degrees of visual angle. With this in mind, we would expect the effects predicted by space-based theories to be mediated by the object properties of the relevant stimuli.

Space-based attention theories also make predictions about the effects of more widely separated stimuli. Researchers have found that, in general, the more widely separated in space two elements are, the more difficult it is to shift attention between them. If attention does act as a spotlight, and two items of interest are more widely separated than the beam of the spotlight, then one would expect a penalty to performance to move the spotlight from one source to the other. In fact, this penalty is observed whether the movement of attention requires eye movements or not. Eriksen and Yeh (1985) attempted to quantify the time it takes to move a tightly focused beam of attention and arrived at a figure of 70 msec. A further contribution was made by Wickens (1992), who proposed the construct of "information access effort" (IAE). This

construct incorporates the time to move attention, the eyes, and the head. The greater the IAE imposed on a pilot by a given display layout, the fewer attentional resources should remain for the performance of the flying task. If those resources are being heavily taxed (i.e. workload is high), increasing IAE would be expected to decrease performance.

Several studies have reported a non-uniform decrease in performance with increasing physical separation (Andre & Cashion, 1993; Martin-Emerson & Wickens, 1992; Sanders, 1970; Sanders & Houtmans, 1985; Schons and Wickens, 1993). Sanders (1970) introduced terms which describe the points of discontinuity in this function. He described a stationary field, where no eye movement is required to view two elements; an eye field, where an eye saccade alone occurs; and a head field, where the eye saccade is accompanied by a head movement. Other studies have attempted to quantify the spatial breakpoints between these fields.

One such study was performed by Martin-Emerson and Wickens (1992). They used HUD-like tasks (tracking and detection) arrayed in the vertical visual field. Their findings supported a three-segment model for IAE, with the segments corresponding to the Sanders (1970) breakpoints. Within the stationary field, they found that IAE remained at a low and constant level, since necessary information could be obtained from both sources without a visual saccade. They noted that the size of this field is affected by the sensory quality of the information sources, with larger and more easily discernible stimuli resulting in a larger stationary field. The particular stimuli used in this study resulted in a stationary field estimated to be 6.4 degrees in diameter. The researchers found that IAE increased when the eye field was entered, but that it remained relatively constant throughout this field. They hypothesized that the ballistic nature of eye saccades results in a cost for getting the saccade started, but little cost for lengthening that saccade. The breakpoint between the eye and head field in this study was approximately 22.5 degrees. Within the head field, IAE increased in a linear fashion with increasing spatial separation.

In order to interpret the findings of the preceding study in terms of expected performance differences between HUD and head-down presentation, an estimate of the angular separation between typical aircraft head-down displays and the out-the-window view is necessary. Not only does this separation vary considerably between aircraft types, however, it also varies within a given aircraft depending on the task of interest and therefore the instrument(s) which are relevant

to that task. Bearing this in mind, an estimate was made by measuring the head-down separation of the attitude indicator in a Frasca 142 simulator. This procedure produced a value of 24 degrees. Clearly, this estimate falls outside the stationary field, suggesting that a HUD which keeps the scan to the far domain within the stationary field will show a performance advantage over head-down presentation. If the HUD to out-the-window scan falls outside the stationary field, however, the benefit may not be evident due to the ballistic nature of saccades in the eye field.

Another relevant experiment was performed by Teichner and Mocharnuk (1979). They noted that moving elements closer together in space did reduce IAE, but that this benefit was offset by the costs of more difficult search in a more dense environment. This finding illustrates the predictions of space-based theories about the effects of decreased spatial separation like that found in HUDs: (1) a performance benefit from shorter visual scans and (2) a performance decrement from clutter.

Before leaving the topic of space-based and object-based attention theories, it is important to return to the Kramer and Jacobsen (1991) study. This study is of particular relevance because its focus was not restricted to one of the two areas. Rather, Kramer and Jacobsen recognized that object-based and space-based theories have joint predictions and sought to investigate how they interact. Their paradigm manipulated both closeness in space and belongingness to a common object and examined the effects on focused attention. Their results concluded that both features of attention were operating, but that space-based effects played a more dominant role.

Ecological Psychology

A third area of particular relevance to the present study is Ecological Psychology. Ecological Psychology is a school of psychology whose practitioners have sought to examine human behavior in more realistic settings than the tightly controlled laboratory environment in which many cognitive psychology experiments have taken place. Since all of psychology research ultimately seeks to explain, predict, or control human behavior in real-world settings,

the Ecological Psychology literature provides an excellent complement to that reviewed in the preceding pages.

A notable difference between many of the laboratory studies previously discussed and a "real world" aircraft cockpit is that in the laboratory studies, subjects were presented with a relatively simple and static stimulus set, whereas a pilot flying an aircraft sees an exceedingly complex scene rich in motion, detail and texture. Furthermore, the field of view of the computer monitors used in many traditional psychology experiments represents only a small fraction of the field of view presented to the pilot of an aircraft. As a result, mechanisms which play an important part in actual flying performance may well have been overlooked in much of the traditional psychology literature. One such mechanism may be the spatial orientation information conveyed by large areas of peripheral vision.

Consider the following: when the world outside the cockpit is visible, foveating on HUD imagery places more of the outside scene within the peripheral visual field than does foveating head-down. Perceiving changes in the orientation of the true horizon is an essential element of the flying task. This perception can be gained through the visual, proprioceptive (seat-of-the-pants), or vestibular senses. Of the three, inputs from the visual system are by far the most reliable (Sventek, 1990). Visual perception of such changes can be gained either by viewing the visible horizon or from an implicit horizon specified by compression or perspective gradients (Gibson, 1979; Lintern & Liu, 1991). Each of these mechanisms can be supported by peripheral as well as foveal vision. Previc (1990) found that spatial orientation information from peripheral vision can be processed pre-attentively. Previc's findings are consistent with those of Weinstein and Wickens (1990), who add that information relevant to control of ego-motion is especially well-suited to this form of pre-attentive processing. The decrease in the portion of the peripheral visual field filled by the outside environment which results from foveating head-down should therefore decrease the amount of orientation information processed preattentively. This line of reasoning is supported empirically by a flight test report on a HUD being manufactured by Flight Visions, Inc., and being marketed for corporate aircraft. The test pilots reported that the additional visual cues afforded by the head-up location of the display helped them "to more rapidly detect deviations from a desired attitude or course" (Tripp, 1992).

Whereas the preceding argument addresses the effects of peripheral vision when the pilot is flying with visual reference to the ground, a second argument can be constructed concerning the transition to landing phase of flight. This phase begins late in an instrument approach, as the aircraft is approaching decision height or minimum descent altitude (the height or altitude below which the pilot may not proceed for a landing unless the runway is in sight), where the pilot expects to break out of the clouds. As elements of the far domain begin to become visible, they will appear to move relative to the aircraft frame of reference, either as a result of the aircraft's forward motion, or as a result of changes in the aircraft's attitude. Because the rods which comprise most of the periphery of the retina are very effective at detecting motion (O'Hare & Roscoe, 1990), the appearance of these far-domain elements should be noticed if they fall within the peripheral visual field. As was pointed out in the preceding argument, head-down foveation decreases the amount of the peripheral visual field filled by the outside scene and should therefore result in a transition-to-visual-references performance advantage for the HUD. This argument also receives empirical support from pilot reports. According to a test pilot of the U.S. Air Force F-16 Fighting Falcon, "an approach to minimums...is another area where the HUD really shines. Since you're already looking through the HUD to fly the approach, you're the first to know you've broken out" (Dryden, 1993, p. 19).

Cognitive capture

Perhaps the most turbulent area of the literature relevant to HUDs involves the possible existence of a phenomenon which Weintraub and Ensing (1992) have referred to as cognitive capture. They ask:

> Might the HUD symbology be so compelling that gazing in the proper direction (head up) and focusing at the proper distance (far away) are offset by the inability of the pilot to switch attention from HUD symbology to the environment? The evidence is meager, but interest is waxing not waning. (p. vi)

One of the earliest studies on which such speculation is grounded was performed by Neisser and Becklan (1975). Their subjects viewed the images of two video games superimposed on a single screen. The study found that subjects attending to one game did very poorly at detecting events in the other game, even when those events were quite salient. A later study, however, found that

with practice subjects did become better at simultaneously attending to two superimposed images (Becklan & Cervone, 1983).

The first stirrings of the cognitive capture debate specific to the aviation domain can be traced to the seminal study carried out by Fischer, Haines and Price (1980). Fischer, et al. used a 727 simulator with commercial airline pilots as subjects. The most frequently cited portion of their results describes what happened when their subjects were presented with an unexpected obstacle on the landing runway, a widebody jet apparently taxiing into takeoff position. On these trials, "mean response time to the runway obstacle was longer with HUD than without it (4.12 vs 1.75 sec), and two of the pilots did not see the obstacle at all with the HUD" (p. 1). In contrast, other evidence in this study, along with some others, refutes the concern that HUD cognitive capture is a strong and pervasive effect. In the discussion of the runway obstacle results, Fischer, et al. point to the format difference between the HUD and the HDIP to which it was compared as the possible culprit. They state that with the HUD, the most accurate source of guidance late in the approach was the display, whereas with the HDIP, the most accurate source was the outside view. This fact ensured that subjects in the HDIP condition would focus attention on the runway sooner than would the subjects in the HUD condition, which would logically result in earlier detection of the runway incursion. A further reason to view the Fischer, et al. incursion findings with some skepticism involves the miniscule statistical power of those results. Because an experimenter pointed out the runway obstacle to two subjects, only two uncompromised head-down and four head-up trials remained.

Another manipulation carried out in the Fischer, et al. study involved programming the instrumentation (HUD or HDIP) to supply erroneous information about the lateral position of the localizer beam, analogous to a "bent beam" malfunction of a real-world Instrument Landing System (ILS). When the runway appeared, it was displaced from the position which the flight instruments had led the pilots to expect. Fischer et al. report that upon breakout, "the runway was such a strong stimulus that seven of the eight pilots reported abandoning the HUD for (external) visual information and making the substantial lateral correction necessary to land". Boucek, Pfaff, and Smith (1983) employed an almost identical ILS offset scenario. In personal communication reported by Weintraub and Ensing (1992), George Boucek concluded that "pilots

were *NOT* bound to the HUD by cognitive capture; rather they responded to the real world quickly and appropriately when it became visible" (p. 107, emphasis in original).

Returning to the earlier quote from Weintraub, what do these results have to say about the "inability to switch attention from HUD symbology to the environment" which Weintraub hypothesized? The lateral ILS offset portion of Fischer et al. and the comments of Boucek seem to refute the contention that HUDs *always* trap attention. The runway obstacle findings of Fischer et al., however, suggest that HUDs might sometimes trap attention when cues in the environment are less salient.

An additional experiment relevant to the cognitive capture debate was carried out by Larish and Wickens (1991). Information in this study was presented via two color monitors vertically stacked 24 degrees apart and both collimated to optical infinity by Fresnel lenses. The format of the flight instruments was the same in both the head-up and head-down conditions. Unlike most of the studies reported in the literature, therefore, this study was not confounded by collimation or format differences. Dependent measures included tracking performance and the latency of responses to both expected and unexpected events. Larish ، .d Wickens found no differences in tracking performance between the head-up and head-down conditions. They also found that subjects responded to a master warning annunciator more rapidly when flying head-up than when flying head-down. Conversely, response to an unexpected windshear warning was slower for head-up than for a head-down presentation. Response to a runway incursion was also slower in the head-up condition. Larish and Wickens reconciled these divergent effects of display location by hypothesizing that the HUD facilitated detection of expected events, but impeded detection of unexpected events. Lower expectation was hypothesized to affect top-down processing through an upward shift in the response criterion for detection. Such a shift would logically lead to amplification of the negative influence of clutter.

Some skepticism of the Larish and Wickens findings is warranted, however, since the low fidelity of simulation may have deprived subjects of wide field of view flow gradients in the environment which may be important in delineating the distinction between HUD symbology and the far domain. Such concerns are in large part allayed, however, by the findings of Wickens, Martin-Emerson, and Larish (1993). This study was a follow-up to the Larish and Wickens (1991) experiment and employed a wide field of view flight simulator which generated

a highly detailed outside scene. Wickens, et al. (1993) replicated most of the effects evident in the earlier study, including HUD advantages for both flight path control and detection of an expected event. The study did not, however, replicate the statistically reliable HUD penalty for incursion detection which was in evidence in Larish and Wickens (1991). One possible explanation for this is based on the fact that the response times observed by Wickens, et al. were quite long (22.47 sec for head-up and 16.25 sec for head-down). This suggests that the stimuli which signalled the necessity of a go-around may have been perceived as somewhat ambiguous by the subjects, and that the variance introduced by this ambiguity may have smothered the underlying performance differences.

Although the evidence in this area is by no means clear-cut, at least two logical arguments explaining why head-up display may disrupt monitoring for and detection of certain kinds of infrequent events have been advanced. The first argument speculates that head-up display disprupts normal scanning patterns in which switches of attention are driven by visual saccades. Stokes and Wickens (1988) suggest that pilots flying with a HUD partition the world into near and far channels and shift attention between the two in a serial manner, just as they must do when flying with a HDIP. In the HUD condition, however:

> pilots presumably are aware that they *must* sample, since physical constraints on peripheral vision prevent outside information from registering while they are head-down. Therefore, fairly rigid and optimal scanning strategies will be invoked to check the far domain of the outside world. This optimal sampling may break down when scanning is no longer required in the HUD. (p. 399)

The second mechanism by which decrements in monitoring and detection of infrequent events may arise is the confusion and clutter effect already discussed in the preceding section on space-based theories of attention.

In summary, the literature is divided regarding its predictions about whether superimposition of HUD symbology is desirable. Object-based models of attention predict that superimposition of conformal HUD imagery is good. Space-based models of attention suggest that both very small and very large separations of information sources are bad. Ecological psychology predicts that a head-up location is advantageous. Finally, the cognitive capture

literature warns that superimposition may make it more difficult to focus attention on one domain to the exclusion of the other.

An experiment was conducted in order to empirically determine how these competing effects trade off against each other in a simulated instrument approach. An additional goal was to enlarge the limited sample of runway incursion response behavior observed in previous studies. A further objective was to test the speculation of Weintraub and Ensing (1992) that collimated HUD symbology presented head-down would support performance as well as the same symbology presented head-up. The study manipulated display location and kept both optical distance and display format constant between head-up and head-down locations. In order to test predictions made by object-based models of attention, half the subjects performed the task with conformal imagery which would fuse as a single object with the far domain when presented head-up. The other half performed with non-conformal imagery. Dependent variables included: (1) tracking error for position (combined vertical and lateral error); (2) tracking error for airspeed; (3) speed of transition from instrument to visual flight references as measured by (a) the latency of subjects' verbal "runway in sight" report and (b) speed of correction from a "bent-beam" symbology-referenced flightpath (similar to Fischer, et al., 1980; and Boucek, et al., 1983) to a visually referenced flightpath; and (4) latency of response to a runway incursion similar to those used in previous studies (Fischer, et al., 1980; Larish and Wickens; 1991; Wickens, Martin-Emerson, and Larish, 1993).

Review of the literature resulted in the formation of two hypotheses. Testing the first of these involved determining whether or not moving the symbology from a head-up to a head-down location would result in a performance penalty for the different kinds of tasks. Testing the second hypothesis entailed finding whether or not any penalty associated with head-down presentation was more severe for conformal than for non-conformal symbology, because in the former case, the move head-down would destroy the integration of the symbology into a single object. Restated in terms of each of the dependent measures, the hypotheses were: (1) position tracking error larger for head-down than head-up, with the head-down cost relatively more severe for conformal than non-conformal symbology; (2) airspeed tracking error larger for head-down than head-up; (3 a, b) both transition latency measures longer for head-down than head-up with no difference between symbology types; and (4) runway incursion response times shorter for

head-down than head-up, with a larger head-up penalty for non-conformal than conformal symbology.

Method

Subjects

Thirty-two paid volunteers, 26 males and 6 females, participated in the study. Subjects had all received flight training from, or were employed by, the University of Illinois Institute of Aviation. All 32 were Federal Aviation Administration (FAA) licensed pilots certified at the Private Pilot level or higher. Fourteen were certified at the Commercial Pilot level or higher, and one was certified at the Airline Transport Pilot level. Nine of the subjects were also Certified Flight Instructors, and 18 held the Instrument Airplane rating. The subjects ranged in age from 19 to 44 years and in total flying time from 70 to 4,250 hours.

Apparatus

Subjects viewed a symbology set and a highly detailed outside scene depicting an Instrument Landing System (ILS) approach to an airport. Both the symbology and the outside scene were projected onto a 3.0 meter wide by 2.2 meter high screen, which the subjects viewed from a distance of 3.0 meters. The outside scene was generated by an Evans & Sutherland SPX500 computer, while the symbology set was generated by a Silicon Graphics, Inc. IRIS Indigo computer. The image projected onto the screen was divided into two areas. A black polygonal region shaped approximately like the instrument panel of an aircraft cockpit occupied the lower portion, while the remainder was filled by the view of the world outside the "aircraft" (see fig. 1).

On head-up trials, the symbology was superimposed on the portion of the outside scene where the runway would appear to a subject maintaining the proper flight path and the instrument panel region was empty. On head-down trials, the symbology set occupied the instrument panel region. The visual angle between the flight path guidance portion of the head-down symbology and the runway scene (when the pilot was on glideslope and at the correct attitude for the approach) was 13 degrees. The visual angle subtended by the instrumentation was 14.7 degrees horizontally and 10.8 degrees vertically. The simulation was controlled by a "Virtual Pilot" yoke and throttle system manufactured by CH Products. Rudder control was not available.

Figure 1. Full view of flight simulator display for a Head-Up / Conformal trial. (note the runway incursion)

Symbology. Two symbology configurations were used, conformal and non-conformal. The two configurations were identical in all respects except two: the way in which they presented lateral flight path guidance, and the presence or absence of a velocity vector. In the conformal configuration (see fig. 2), guidance relative to the localizer course (lateral guidance) was provided by a virtual runway symbol which overlayed and moved in unison with the real runway (see Bray, 1980, for a detailed discussion). In addition, a velocity vector was provided. The velocity vector used information about pitch attitude, angle of attack and crosswind to compute the predicted future position of the aircraft. In the non-conformal configuration (see fig. 3), localizer course guidance was provided by a Course Deviation Indicator (CDI) (Air Force Manual 51-37, 1986). A velocity vector was not incorporated in this configuration. Glideslope (vertical) guidance was conveyed by a Glide Slope Indicator (GSI) in both conditions, although the format of the GSIs differed. The GSI in the conformal condition was a pair of dashed lines adapted from Weintraub and Ensing (1992, p. 72). The GSI in the non-conformal condition had

Figure 2. Conformal symbology set

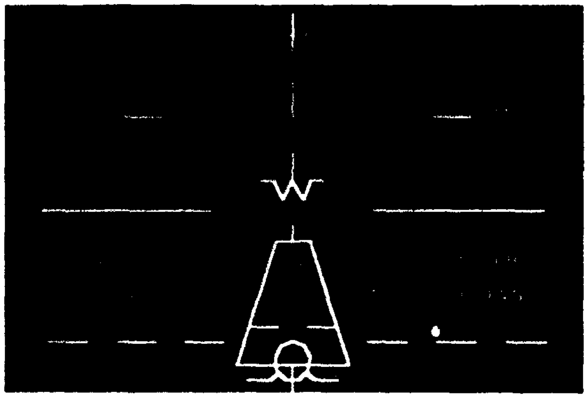
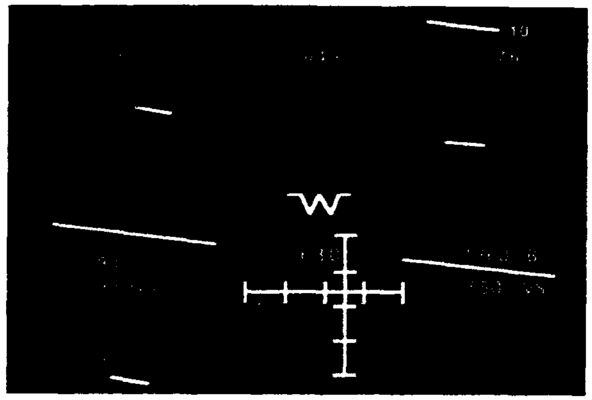


Figure 3. Non-conformal symbology set



a more conventional "needle" format identical to that of the CDI (Air Force Manual 51-37, 1986).

The symbolic runway was categorized as conformal because it overlaid and moved in unison with its far domain spatial analog -- the real runway. The CDI was thought of as non-conformal because it did not normally overlay the runway, and because the mapping between its motion and that of the localizer centerline was not one-to-one. The velocity vector was categorized as conformal. Its far-domain spatial analog was the optical flow expansion point, an optical invariant whose location in the environment is marked by the point where there is no flow, but from which all flow appears to radiate (Gibson, 1979; Wickens, 1992a).

It is important to note that the distinction drawn between the two symbology sets refers only to the means by which lateral flight path guidance was presented. Both sets included some non-conformal as well as some conformal elements. The conformal element common to both displays was the horizon line (the two large horizontal lines near the center of the display) (see fig. 2). In addition, two elements may be defined as "virtually conformal" because they overlay positions in space that had direct spatial relevance to the pilot, even though those positions were not occupied by real objects. These were the pitch ladder (shorter lines parallel to the horizon line), and the "W"-shaped miniature aircraft symbol (sometimes called a boresight) (see fig. 2). The remaining elements were non-conformal. Clockwise from the upper left of figure 2, they were: Distance Measuring Equipment (DME) readout, magnetic heading, percent of rated engine RPM, barometric altitude, vertical speed, radar altitude (near the center), groundspeed, and

airspeed. Another non-conformal display element found on both displays consisted of a text warning message which appeared only if airspeed deviated substantially from the desired value.

Dynamics. The dynamics of the simulation did not attempt to replicate those of any particular aircraft type. In general, however, they mimicked those of a real aircraft. For example, if the subject increased the pitch attitude by pulling back on the yoke and failed to add power, the airspeed would decrease.

The CDI and GSI "needles" in the non-conformal condition moved in the customary way, i.e. GSI below center meant that the glideslope was below the aircraft's present position and CDI left of center meant that the localizer course was left of the aircraft's present position. The indication that the aircraft was on-course and on-glideslope was that both needles were centered. In the conformal condition, the on-glideslope indication was the dashed GSI lines vertically aligned with the fixed-distance markers (markings which appeared 1,000 feet from the approach end of both the symbolic runway and the "real" runway). Just as in the non-conformal condition, if the GSI was above the desired position, it indicated that the glideslope was above the aircraft's present position. Localizer course guidance in the conformal condition was conveyed by the position and perspective of the symbolic runway. Subjects maintained the proper course by executing the same responses to changes in appearance of this element as they would to identical changes in appearance of the "real" runway.

The airspeed warning messages mentioned above appeared only if airspeed differed greatly from the desired value of 90 knots. If airspeed decreased to 75 knots or below, a "STALL WARNING" message would appear. If airspeed increased to 115 knots or above, a "GEAR OVERSPEED" message would appear. When such a message appeared, it occupied the upper center of the symbology set. The the letters comprising the message were drawn in the same font size as were the digits for the various non-conformal display elements (airspeed, vertical speed, etc.).

The dynamics of the simulation also included turbulence, the magnitude and direction of which was determined by the summation of randomly generated sinusoids. This turbulence affected pitch, roll, and yaw attitude, as well as "heave" in aircraft position (analagous to the effect of flying through updrafts and downdrafts).

Procedure

Symbology type was manipulated between subjects, with 16 subjects randomly assigned to each level. Subjects were first grouped by total flight hours, then randomly assigned to the experimental treatments. The result was that the median number of total flight hours was approximately equal in each treatment. Display location (head-up versus head-down) was blocked within subjects. The presentation was counterbalanced so that, within each symbology configuration, eight subjects flew with head-up followed by head-down display location, and eight flew with the opposite order.

Each subject participated in two sessions, which were spaced at least one day apart. Prior to beginning each of the two sessions, subjects were required to read a set of instructions specific to the symbology treatment to which they were assigned (see appendices 1 and 2). Each subject also received a verbal briefing which served both to explain the functioning of the symbology and to answer subjects' questions. In the first session subjects flew 16 approaches (trials), the first eight of which were used for practice. In the second session they flew 20 approaches, the first two of which were used for practice (see fig. 4).

Figure 4. Experimental Design for the 50% of subjects presented with head-down before head-up

Day 1

<table>
<tr><td colspan="2">Block 1
Trials 1-8</td><td colspan="2">Block 2
Trials 9-16</td></tr>
<tr><td>Down</td><td>Up</td><td>Down</td><td>Up</td></tr>
<tr><td colspan="2">PRACTICE</td><td colspan="2">DATA COLLECTION</td></tr>
</table>

Day 2

<table>
<tr><td colspan="2">Block 3
Trials 1-2</td><td colspan="2">Block 4
Trials 3-20</td></tr>
<tr><td>Dn</td><td>Up</td><td>Down</td><td>Up</td></tr>
<tr><td colspan="2">PRACTICE</td><td colspan="2">DATA COLLECTION</td></tr>
</table>

Weather conditions constituted one independent variable. This variable took on five levels, summarized in table 1. As subjects descended below the cloud base, visibility increased from zero to a value such that the runway environment could only barely be discerned (except for level E). Discriminability of the runway and its surroundings increased steadily as the aircraft flew nearer to the runway. Overall luminance of the visual scene was controlled at a relatively constant level so that subjects would not be able to rely on a general change in brightness to know when the runway would be visible. Subjects were instructed that the Decision Height for each approach was to be 200 feet. In accordance with standard instrument procedures, subjects were instructed to execute a missed approach if they reached DH and determined that "visual reference to the runway environment [was] insufficient to complete the landing [or] that a safe landing [was] not possible" (Airman's Information Manual, 1988, para. 404a). The missed approach was initiated by simultaneously raising the nose and advancing the throttle to full power.

Table 1. Ceiling and visibility levels

Level	Ceiling (feet)	Visibility (statute mi.)
A	340	1.0
B	285	0.8
C	220	0.8
D	50	0.125
E	220	2.0

The visibility manipulation was carried out in order to force subjects to divide their attention between the symbology and the outside scene. During the first part of the approach, when the aircraft was in the clouds and not expected to break out in the near future, subjects were expected to focus attention solely on the symbology. As DH was approached, subjects were expected to incorporate the out-the-window view into their crosscheck in anticipation of the appearance of the runway. Following visual acquisition of the runway environment, subjects were still expected to divide their attention by monitoring the outside scene for position information and the symbology for airspeed information. The varying visibility levels ensured that subjects did not know when or if they would break out of the clouds prior to DH. Of the 36 trials of the experiment, eleven were visibility level A, ten were level B, ten were level C, four were level D, and one was level E.

Three steps were carried out to enable the experimenter to assess when (and therefore how rapidly) subjects had transitioned from instrument to visual flight references. The first was

to require subjects to verbally report when they had the runway in sight. The experimenter recorded the time of this report with a keypress.

The second step was to simulate a "bent-beam" malfunction of the ILS similar to that found in previous studies (Fischer, et al., 1980; Boucek, et al., 1983). This procedure involved programming the symbology to behave as if the runway and glidepath were located 200 feet to one side or another of their actual positions and was introduced on 12 of the 36 trials. The value of this measure was established in two ways, one objective and one subjective. The objective measure was produced by a computer algorithm which looked for a heading correction toward the real runway of three degrees or more, and then recorded the time of the aileron deflection which resulted in that correction. This was supplemented by subjective examination of a top view of the path flown by the subject. The experimenter determined the location of the bend in the path which marked the transition from the symbology-referenced path to the outside-scene-referenced path and used this evaluation as a check on the accuracy of the computer algorithm.

The third step by which transition to the outside scene was assessed was by means of an unexpected runway incursion similar to those in previous studies (Fischer, et al., 1980; Larish and Wickens, 1991; Lauber, et al., 1982). This incursion occurred once per subject, on the last trial of the experiment. On this trial, a widebody jetliner taxied into takeoff position on the runway on which the subject was about to land. The visibility on this trial (weather condition E) was such that the jetliner was clearly visible. This measure was collected by recording the latency between the time subjects broke out of the clouds and the time at which they initiated a go-around. This was inferred by examining the data to determine when two conditions were satisfied: the throttle was advanced to full power and the nose was raised. Since this event was only presented on the final trial of the experiment and display location was counterbalanced, only eight subjects perceived the event in each of the four conditions defined by location X symbology type.

At the end of the experiment, subjects completed a questionnaire (see appendix 3) on which they indicated the display location they preferred. This form also assessed whether or not subjects were surprised by the runway incursion and whether or not they initiated a go-around as soon as they saw that the airliner had taxied onto the runway.

Results

Position tracking

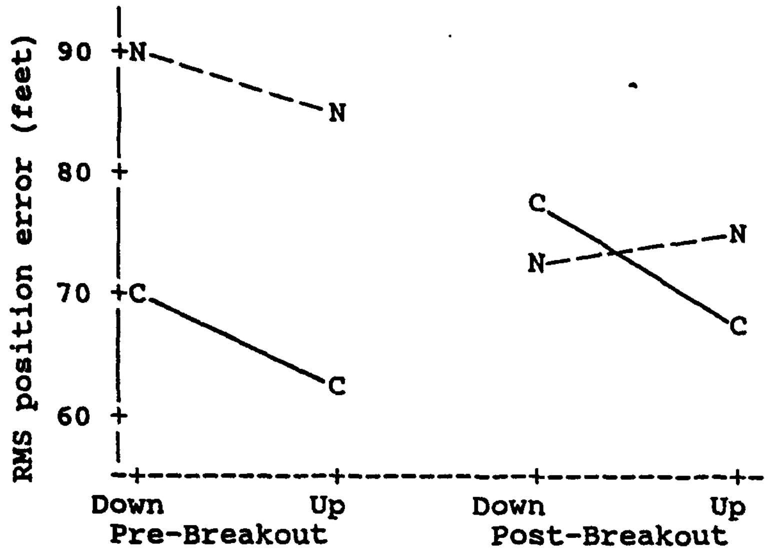
Position tracking error was calculated by adding the vertical Root Mean Square Error (RMSE) to the horizontal RMSE. RMSE was also used as a measure of airspeed tracking error. Analysis of the raw data for positition and airspeed error showed distributions which departed substantially from the common statistical assumptions of normality and homoscedasticity. These departures were remediated through two measures: data selection and variance-stabilizing transformation. Screening for candidate outliers revealed four of 1,180 position observations and five of 1,477 airspeed observations which lay further than five standard deviations from their respective means. In each case, the direction of deviation was toward poor performance. It was reasoned that these observations constituted samples of behavior that were not representative of the competent, professional airline and military pilots to whom the present study attempts to generalize. As a result, all nine observations were removed. The remaining tracking error data were then subjected to a logarithmic transform. The resulting distribution closely approximated normality and exhibited stable variance across all levels of the independent variables.

Subsequent analysis of the position tracking data showed a distinct difference between pre-breakout and post-breakout performance (see fig. 5 and table 2). Prior to breakout, tracking performance in the head-up condition was superior to that in the head-down condition, a relationship which held for both symbology configurations. No interaction between symbology and location was evident, that is, the cost of moving both types of symbology was about the same. After breakout, however, this pattern changed. An interaction appeared in which performance differences between non-conformal display locations disappeared and the advantage for head-up presentation of conformal symbology remained.

<u>Table 2.</u> Summary statistics for position tracking error

Pre-Breakout	df	F	p-value
Main effect of location	1, 795	16.4	$p<.0001$
Location X symbology	1, 795	0.8	$p<.37$
Location, symblgy=Conf	1, 397	5.9	$p<.001$
Location, symblgy=Non-conf	1, 398	10.6	$p<.02$
Post-Breakout	**df**	**F**	**p-value**
Main effect of location	N/A	N/A	N/A
Location X symbology	1, 313	5.7	$p<.02$
Location, symblgy=Conf	1, 149	8.6	$p<.004$
Location, symblgy=Non-conf	1, 164	0.4	$p<.56$

Figure 5. Position Tracking Error



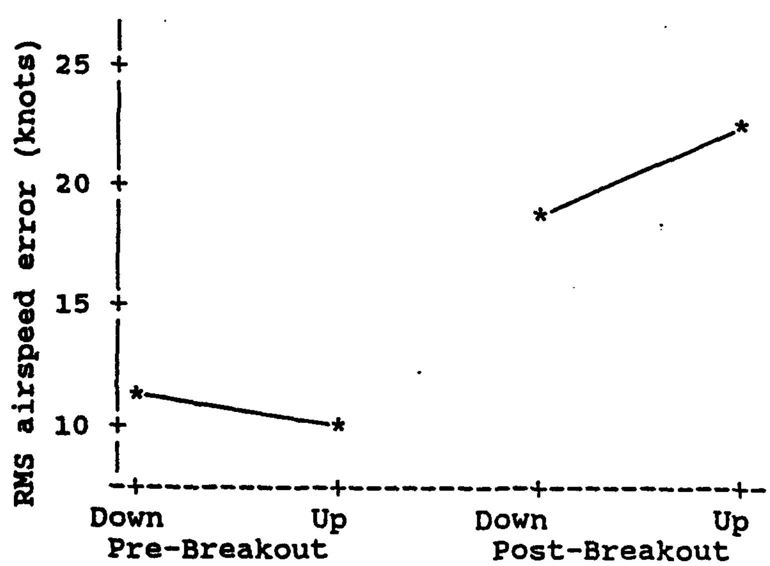
Airspeed Tracking

During the pre-breakout period, airspeed error (see fig. 6 and table 3) showed no significant differences between head-up and head-down location. After breakout, the best performance was associated with the head-down presentation.

Table 3. Summary statistics for airspeed tracking error

Pre-Breakout	df	F	p-value
Main effect of location	1, 794	1.87	p<.17
Post-Breakout	**df**	**F**	**p-value**
Main effect of location	1, 610	4.98	p<.03

Figure 6. Airspeed Tracking Error



Runway in sight report latency

The mean latencies of reporting the runway in sight are plotted in Figure 7 and the relevant statistics are shown in Table 4. A main effect of location was present indicating an advantage for head-up presentation. No interaction between symbology and location was in evidence.

Table 4. Summary statistics for runway in sight report

	df	F	p-value
Main effect of location	1, 648	3.0	p<.08
Location X symbology	1, 648	0.3	p<.58
Location, symblgy=Conf	1, 310	2.9	p<.09
Location, symblgy=Non-conf	1, 338	0.6	p<.43

Figure 7. Runway in sight report latency

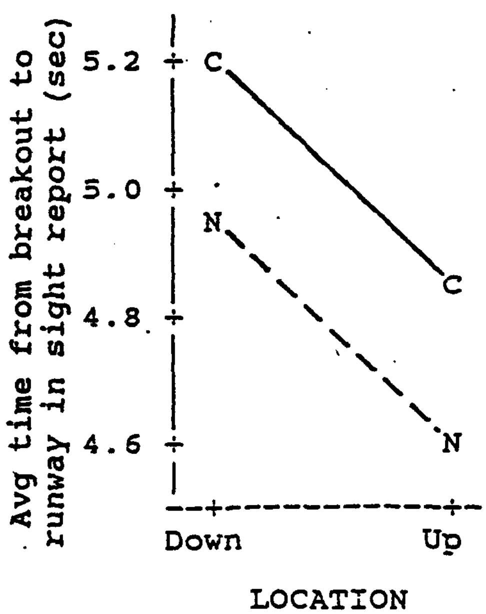
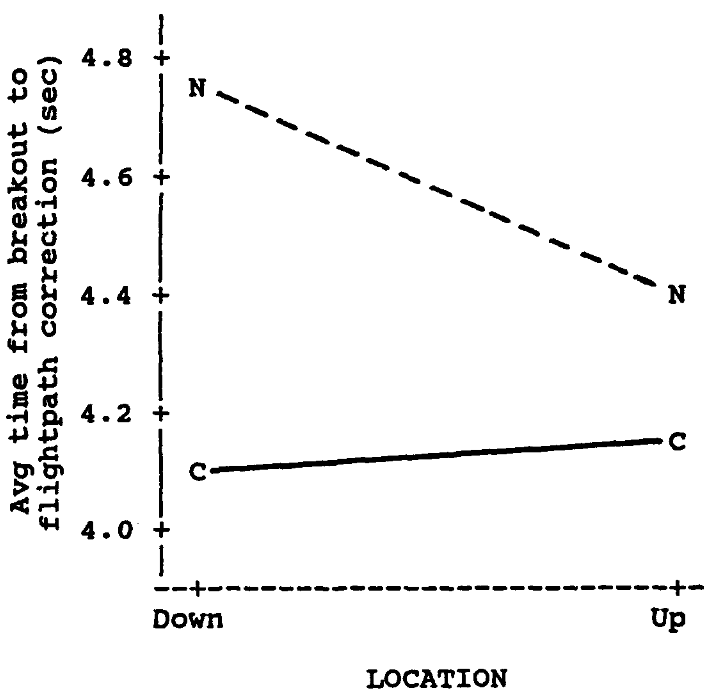


Figure 8. Flightpath correction latency



Flightpath correction latency

For those trials in which the localizer beam was offset from the true centerline of the runway, a measure was collected for the speed with which subjects transitioned from the

symbology-referenced flightpath to a visually referenced one. Analysis of these data showed no significant main effects or interactions (see table 5 and fig. 8).

Table 5. Summary Statistics for Fligthpath Correction Latency

	df	F	p-value
Main effect of location	1, 267	0.35	p<.56
Location X symbology	1, 267	0.04	p<.83
Location, symblgy=Conf	1, 130	0.29	p<.59
Location, symblgy=Non-conf	1, 137	0.08	p<.77

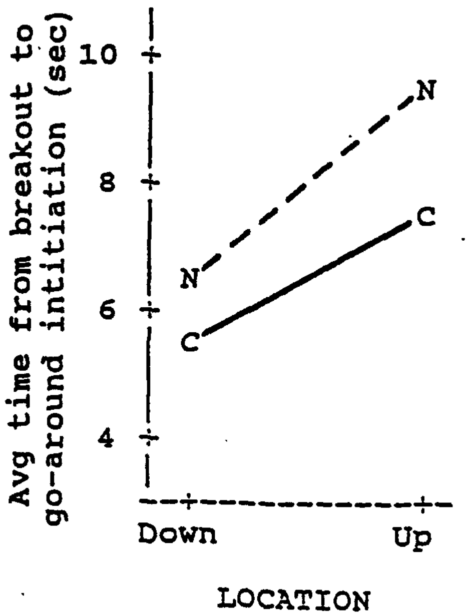
Questionnaire data and incursion response latency

Analysis of responses to the post-experiment questionnaire revealed that eleven of the subjects assigned to the non-conformal condition preferred head-up location, three preferred head-down location, and two had no preference. All 16 subjects assigned to the conformal condition preferred the head up location. One subject indicated that she was not surprised by the runway incursion, since she had participated in the Larish and Wickens study. Six others stated that they did not initiate a go-around immediately after seeing the airliner taxi onto the runway. Their typical reasoning for this was that the 90 knot approach speed and 200 foot decision height provided them with several seconds in which to assess whether the airliner would take off in time for them to land behind it. Prior to statistical analysis of the runway incursion data, the observations for these seven subjects were discarded. The data (see table 6 and fig. 9) showed a significant main effect of location favoring the head-down presentation thereby replicating the earlier findings of Fischer, et al. and Larish and Wickens. This effect was of approximately equal magnitude for both symbology sets.

Table 6. Summary statistics for incursion response latency

	df	F	p-value
Main effect of location	1, 21	4.8	p<.04
Location X symbology	2, 21	1.4	p<.27
Location, symblgy=Conf	1, 9	0.6	p<.47
Location, symblgy=Non-conf	1, 12	4.2	p<.06

Figure 9. Incursion Response Latency



Discussion

Position tracking

Pre-breakout: The strong advantage shown for head-up presentation prior to breakout can be explained by the fact that, during this phase of flight, subjects had to scan repeatedly between the symbology and the portion of the out-the-window view where the runway would appear. This scanning demanded a certain level of IAE. Since the subjects were engaged in a challenging continuous manual control task at the same time, the larger the IAE demanded by the scan, the fewer resources would remain available for the continuous manual control task. The poorer performance in the head-down condition would therefore seem to indicate that the IAE demanded by the head-down location was higher than that demanded by the head-up location.

With this result in mind, let us return to the attention literature. Space-based theories predicted two effects in opposite directions: (1) a head-up benefit due to reduced scanning and (2) a head-up penalty due to confusion and clutter. Object-based theories predicted a head-up benefit due to object fusion, but only for the conformal symbology. In the pre-breakout phase, the background against the symbology was presented was a uniform grey which simulated clouds. Since the far domain was not in view, neither the object fusion nor the confusion and clutter effect could have occurred. The only effect which should therefore remain is the head-up benefit due to reduced scanning.

Recall from the preceding literature review the distinction between the no-scan, eye, and head fields (Martin-Emerson and Wickens, 1992; Sanders, 1970). Recall also that the angular separation between the flightpath guidance portion of the head-down symbology and the portion of the out-the-window view where the runway normally appeared was 13 degrees, a figure which falls squarely between the 6.4 degree and 22.5 degree values found to demarcate the eye field by Martin-Emerson and Wickens (1992). The pre-breakout benefit for head-up presentation which appeared in the present study can therefore be explained by space-based attention theories, given that the head-up symbology to out-the-window scan fell within the no-scan region and the head-down symbology to out-the-window scan fell within the eye field. Due to the ballistic nature of eye saccades, the performance decrement imposed by the 13 degree scan should be very close to that imposed by a scan in the vicinity of 20 -22.5 degrees. Consequently, in spite of the fact that

the apparatus in the present experiment prevented use of a separation more typical of an aircraft cockpit (around 24 degrees), the results should nonetheless generalize to actual aircraft, particularly those with display layouts at the lower end of the separation range.

Post-breakout: The postition tracking data for the post-breakout phase shows that the head-up advantage disappeared for non-conformal symbology, but persisted for conformal symbology. This interaction can be explained by an additive model of the three effects described earlier: head-up benefit due to reduced scanning, head-up penalty due to clutter, and head-up benefit due to object fusion. Since the distances over which scanning took place were identical in this phase to those in the pre-breakout phase, the head-up advantage due to reduced scanning should have remained. This advantage should have accrued equally to conformal and non-conformal symbology. The second effect, head-up penalty due to clutter, should have appeared since the contours of the outside scene came into view in this phase. This effect should also have acted independently of symbology. The third effect, head-up benefit due to object fusion, should only have come into play for the conformal symbology. The data for non-conformal symbology suggests that the two competing effects of reduced scanning and clutter were roughly equal in magnitude, resulting in a sum near zero. Such an outcome is consistent with the findings of Teichner and Mocharnuk (1979). Examination of the conformal symbology data suggests that the object fusion benefit nullified the clutter cost, preserving (and even slightly enhancing) the head-up advantage seen in the pre-breakout phase. This conclusion replicates Kramer and Jacobsen's (1991) finding that, even when a distractor element is brought closer than one degree of visual angle from a target element, performance-degrading effects can be avoided if the distractor and target belong to different objects. This observation stands in contrast to the pure space-based attention research finding that processing of stimuli within the one degree minimum resolution of the attentional spotlight is unavoidable (Eriksen & Eriksen, 1974; Eriksen & Hoffman, 1972, 1973).

Airspeed tracking

In seeking to understand the results for the airspeed tracking measure, it is important to note that the critical display element for this task was the digital airspeed readout. Since this element was the same in both display configurations, analysis of this measure was collapsed

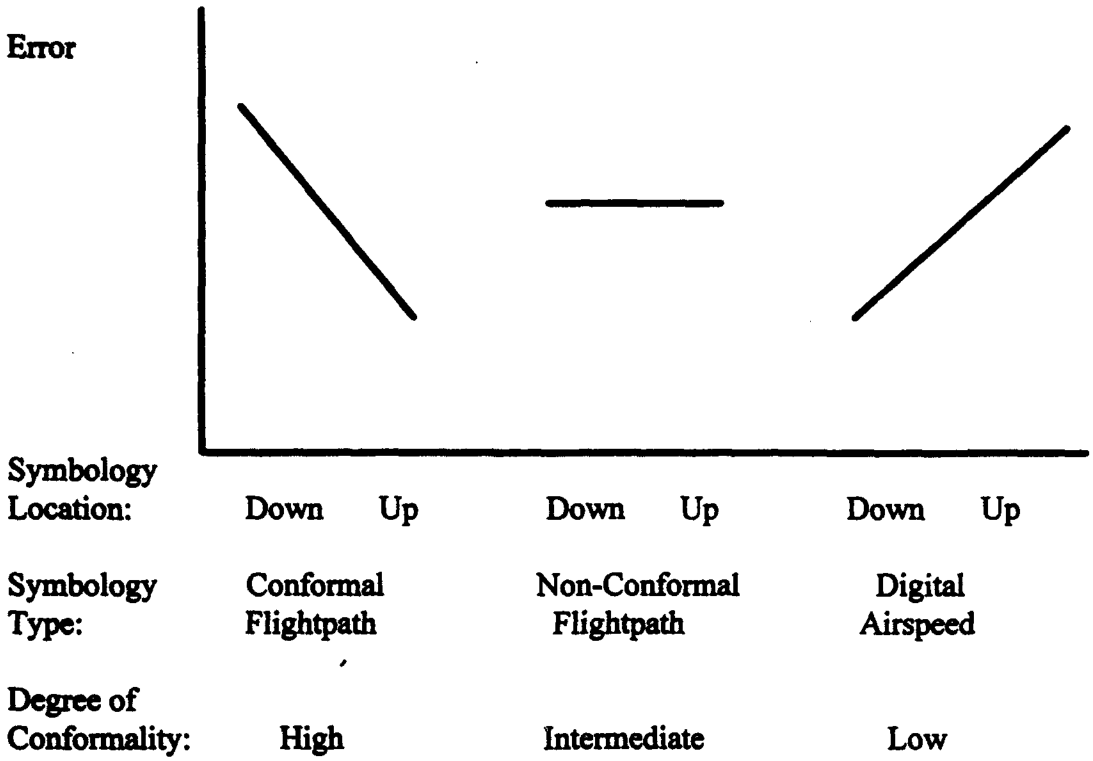
across the two. Because the airspeed display was a non-conformal symbology element (a digital readout), the attention literature would lead us to expect effects very similar to those evident in the non-conformal position tracking results, i.e., a distinct advantage for head-up presentation prior to breakout and rough equivalence of head-up and head-down performance after breakout. The obtained results were not entirely consistent with these expectations. Prior to breakout, there was a trend in means favoring head-up presentation, but this difference was not statistically significant. After breakout, a clear and statistically reliable penalty for head-up presentation appeared. Again adopting the additive effects model, it would seem that the same effects are still at work in this phase, but that the magnitude of at least one of the effects has changed from what it was in the non-conformal postition tracking measure. Two possible explanations for this are advanced. The first hypothesizes that a reduction in the head-up benefit due to reduced scanning is responsible, and the second implicates a difference in the head-up benefit due to object fusion.

The first explanation involves the fact that the airspeed display was discrete and the flightpath guidance displays were continuous. Only those disturbances which changed the airspeed by one knot or more were visible, whereas very minor disturbances in flightpath error were visible. This could have resulted in the bandwidth of information being higher for flightpath error than for airspeed information. This, in turn, may have necessitated more frequent foveation of the flightpath error than the airspeed symbology and hence a greater impact of scanning penalties. Since the total head-up scanning benefit should be the product of the number of scans and the benefit on each scan, it would appear logical that the total head-up scanning benefit (head-down penalty) would be greater for the flightpath error than for the airspeed information. This reduction in benefit to head-up presentation can explain both the pre-breakout and post-breakout differences between the non-conformal position tracking data and the airspeed data. Prior to breakout, a reduction in head-up scanning benefit could be responsible for the change from a statistically significant head-up benefit (to position tracking) to a non-significant trend for head-up benefit (for airspeed tracking). After breakout, the smaller head-up scanning benefit (to airspeed) could be expected to lead to the summation of the three effects in the additive model leaning more heavily in the direction of the head-up clutter penalty, an explanation which is consistent with the observed change from no significant difference between head-up and head-down to a significant penalty for head-up.

The second possible explanation for these effects focuses instead on the degree of conformality of the relevant symbology. The construct of conformality can be expanded beyond an "all or nothing" property to incorporate a continuum ranging from fully conformal to partially conformal, to non-conformal. Partially conformal symbology would be that which moves in a way which is spatially meaningful with respect to the far domain, but which does not always overly a far domain spatial analog or move with it in a one-to-one manner in such a way as to produce object fusion. An example of such symbology would be the "crossed needles" of the present study's non-conformal symbology set. To illustrate, consider the vertical "needle", or CDI in figure 3. When the aircraft strays to the left of the extended runway centerline, the CDI deflects to the right. The out-the-window view of the runway also moves to the right. The amounts of these two deflections, however, are not necessarily identical, nor will they be superimposed. Hence, over time, the motion patterns of these two elements (runway and CDI needle) across the display will be positively correlated (as if belonging to a non rigid object). The apparent motion of the runway across the windscreen will be a function not only of the aircraft's position in space, but also of the aircraft's attitude. The motion of the CDI, however, is a function only of the aircraft's position in space. Suppose that the aircraft is established on the center of the localizer beam and its heading is exactly that of the runway. The pilot will see the runway in the center of the windscreen and the CDI will be centered. If a crosswind from the left develops, the pilot must make a heading correction, or "crab" to the left in order to remain on the localizer centerline. After this crab has been established, the runway will appear to the right of where it had in the no-wind condition. Since the aircraft is still on the localizer centerline, however, the CDI will remain centered. This illustrates why the CDI is less than fully conformal. At the same time, it is clearly more conformal than a digital airspeed readout, which does not move in a direction corresponding to the motion of any far domain element.

With this in mind, let us examine the post-breakout tracking performance for conformal position, non-conformal position, and airspeed. Figure 10 represents a schematic depiction of the positional effects across the three levels of conformality. As the figure shows, the slopes of the lines connecting head-down to head-up performance seem to be related to the degree of conformality. It appears that for high conformality, the clutter penalty is overwhelmed by a strong object fusion benefit. For intermediate levels of conformality, the "flexible object"

Figure 10. Post-breakout tracking performance vs. degree of conformality



benefit appears to be just strong enough to cancel out the clutter penalty. For low conformality, the complete lack of an object benefit seems to permit the clutter penalty to manifest itself unchecked.

Runway in sight report latency

The results for this measure show a marginally significant (p<.09) trend towards a head-up advantage for conformal symbology and no significant difference (p<.43) for non-conformal symbology. The statistical power of the comparison might have been higher had it been possible to directly determine the moment at which subjects first saw the runway. Unfortunately, the measurement technique added additional latencies to the one of interest. After seeing the runway, subjects had to remember to say the phrase "runway in sight" and then had to verbalize that phrase. The experimenter had to respond to this auditory stimulus by striking a key. The variability introduced by this concatenation of latencies may have suppressed what might otherwise have been a statistically significant effect. This finding of general head-up advantage is

consistent with a-priori expectations formed by the review of the ecological psychology literature. That is, because subjects in head-up conditions were already foveating on the location in space where the runway would come into view, peripheral vision should have enabled them to detect the appearance of the far domain even when attention was focused on the symbology. Also consistent with expectations was the fact that the trend toward head-up advantage was stronger for conformal than for non-conformal symbology. This could be due to object fusion of the contours of the symbolic runway with those of the real runway. If subjects were focusing attention on the symbolic runway when breakout occurred, then the target stimulus ("real" runway) should have belonged to the same perceptual object. These findings are consistent with those of Duncan (1984), who observed that attention switches will be faster between elements of a single object than between elements of two different objects.

Flightpath correction latency

Analysis of these data showed them to be even noisier than the runway in sight report latencies. Reasons for this include the introduction of variability due to the subjective assessment of flightpath alteration by the experimenter and the differing pilot strategies for correcting to the centerline of the visual runway. The lack of statistical precision engendered by these two factors was exacerbated by the fact that the ILS offset manipulation was introduced on only 10 of 26 trials, thereby reducing the sample size relative to the previous measure. Because of the large variability, no conclusions could be drawn from this measure.

Incursion response latency

The findings for this measure make the present study unique in that, unlike Fischer, et al. (1980), they showed a statistically reliable penalty for head-up presentation (as well as controlling for optical distance and format) and unlike Larish and Wickens (1991), they come from an experimental paradigm employing a relatively wide field of view and high visual fidelity. An additional interesting finding is that the head-up penalty was more severe for non-conformal ($p < .06$) than for conformal symbology ($p < .47$). This reflects in a confirmatory way on the speculation of Martin-Emerson (1993). She suggested that conformal symbology might better "support divided atention and consequently, reduce the potential for attentional capture"

(p. 7) than would non-conformal symbology. The head-up clutter penaltythat was evident in the flightpath and airspeed tracking results appears to be at work in the incursion latency measure as well. However (perhaps due to low expectancy of the runway incursion) neither the head-up benefit due to reduced scanning nor the head-up benefit due to object fusion were able to suppress this clutter effect.

This finding of a HUD cost should be taken into consideration in making future decisions about cockpit display design, but it should not be seen as incontrovertibly damning the HUD. Indeed, recent evidence exists which suggests that the runway incursion results of the present and other simulator-based studies may not be completely generalizable to the real world aircraft cockpit. In personal communication (7 April 1994), Dr. Richard Newman of Crew Systems, Inc., San Marcos, TX indicated that his company had been hired by the FAA to evaluate the possibility of cognitive capture using a Flight Visions, Inc. HUD as part of the flight certification process. In the experiment he described, crews of two pilots each flew real approaches in a Beechcraft King-Air in which the left seat was HUD-equipped and the right seat was not. On certain approaches, a runway incursion was presented and the latency with which each of the crewmembers noted it was recorded. He stated that the left seat pilots, who were flying with the HUD, noted the incursion faster than did the right seat pilots and that, although the specifics of the test are proprietary, this difference was statistically significant at a customary alpha level. While the level of expectancy of the runway incursion held by the crews is not clear, it seems reasonable to believe that this expectancy was no different for copilots than for pilots. Although the inability to scrutinize the methodological details of the study prevents adoption of the results as evidence in the strictest traditions of the hypothetico-deductive approach to science, this study nonetheless serves as a reminder that laboratory research does not always generalize to the real world. It is quite possible that studies in which the symbology and outside scene are both computer generated (and therefore are similar in texture, luminance, etc.) make it more difficult for subjects to parse the visual scene into near and far domains than would be the case in a real aircraft (where the symbology would have a ghostly, computer-generated appearance and the far domain would have the rich texture of tangible physical objects). If this is, in fact, the case, then the cognitive capture effect evident in the present study may be ephemeral, dissolving when behavior is taken outside the laboratory. Furthermore, it needs to be reemphasized that even if

cognitive capture *is* a real phenomenon beyond the laboratory, its manifestation appears under very infrequent circumstances, compared with the continuous benefits provided by the head-up presentation of conformal symbology.

Synthesis

Altogether, the data replicate earlier findings of HUD advantages for flight path control, even when imagery differences and collimation are controlled for. The HUD appears to enable faster transition to visual flight reference, a logical finding in light of the shorter scan from symbology to outside scene. At the same time, the HUD seems to produce a clutter effect which slows down detection of an unexpected far-domain event. In terms of position tracking, there appears to be a larger penalty for moving information from head-up to head-down if that symbology is conformal than if it is non-conformal. The present findings should be of interest both to attention researchers and to aircraft cockpit designers.

The present study found effects which could only be explained by a combination of space-based and object-based theories, a synthesis consistent with the findings in basic research by Kramer and Jacobsen (1991). Space-based theories succeeded in prediction of the head-up benefit which appeared prior to breakout. In addition, they explain the clutter effects which seem to be concomitant with head-up presentation of non-conformal symbology. They were unable, however, to explain the nullification of the clutter cost when symbology formed a perceptual object with far domain spatial analogs, an explanation which was provided by object-based theories. This suggests that a full understanding of work-situtated cognition in settings as complex as an aircraft cockpit can only be attained by integration of the findings of these two categories of research.

The contribution of this study to the domain of cockpit design can best be summed up as an answer to the hypothetical question posed by Weintraub and Ensing (1992): 'what if the HUD benefit is a result not of the superimposed location of the symbology, but rather of the modern format and far optical distance? Might a head-down presentation of HUD-like symbology employing collimating optics retain the HUD performance advantage for precision instrument flying, while avoiding clutter problems from hiding parts of the outside world behind HUD symbology?' The answer given by the present study is that modern symbology and far optical

distance cannot account for all of the HUD benefit noted in previous studies; the superimposed HUD location *is* responsible for a substantial portion of that benefit. Although HUDs are by no means perfect, a superior alternative has yet to surface. Until one does, the prudent course of action would seem to be one of educating HUD users about the imperfections and designing systems to be robust for the errors which are likely to result from them.

Appendices

Appendix 1. Subject instructions for conformal symbology

Subject Instructions
HUD Experiment 94C

• Thank you for participating in this experiment. We're trying very hard to make sure your contribution to this study will translate into meaningful information for the designers of future cockpit displays. As you may know, Head-Up Displays have found their way into both air carrier (Alaska and Northwest airlines) and corporate aircraft. NASA is very interested in determining the appropriate symbology to be presented both head-up and head-down.

• The experiment will consist of flying multiple ILS approaches in weather conditions near published minimums. On some approaches your instrument symbology will be superimposed on the visual world (head-up) and on others it will be positioned head down. The symbology set contains some elements you'll be familiar with, but others which you're not likely to have seen before. Here's how the more novel elements work:

- Information about DME, heading, glidepath, and localizer deviation has been integrated into a "symbolic runway". This is designed to look just like the real runway would from your current perspective if you were not in the clouds. More precise glideslope information can be obtained by looking at the horizontal dashed lines alongside the approach end of the symbolic runway. When you line them up with the two marks you'll see on the symbolic runway, you're on the 3^{o} glidepath.

- Pitch is represented by a "w" shaped miniature aircraft similar to the one in the center of an attitude indicator. By comparing it to the pitch ladder (markings every 5^{o} above and below the horizon line), you can tell where your nose is pointed. Of course, just because your nose is pointed above the horizon doesn't mean you're climbing -- your flight path angle also depends on your angle-of-attack (AOA).

- Information about pitch and AOA has been combined with ground-referenced information (like GPS or INS would give you) about the current winds. All of this is used to present a "velocity vector", which shows where your aircraft is really going. When it's below the horizon, the velocity vector shows where your aircraft would impact the ground if you didn't change your flightpath.

- The altimeter closest to the center of the display shows radar altitude, which is always AGL.

• After you've gotten the controls in a comfortable position, start the trial by pressing the red button under your left thumb. You will start each trial at

Appendix 1 (continued).

1,000 feet AGL, inside of the glideslope intercept point, configured for landing, and establised in a 3^{o} descent. Power will be set to 75% and airspeed will equal 90 knots, which is your desired approach speed. Please try to maintain exactly 90 knots all the way to the ground. You should be able to track the localizer course and glideslope by flying your velocity vector onto the the approach end of the symbolic runway and keeping it there.

• Decision Height on this approach is 200 feet AGL, so when you've descended to within a couple of hundred feet of this altitude you should start bringing the "out-the-window" view into your crosscheck. If you break out of the weather and sight the runway prior to DH, immediately say "runway in sight" and transition to a visual landing. The experimenter will be trying to record the exact moment when you first sight the runway by hitting a key, so please say this phrase promptly and distinctly.

• If you get to 200 feet radar altitude and still don't see the runway, execute a missed approach. As it says in AIM, you should go missed approach if you feel that "1) Visual reference to the runway environment is insufficient to land" or 2) you feel that "a safe landing is not possible" (para. 404a). Execute a missed approach or go-around by pushing the throttle to full power while smoothly raising the nose (8 - 10 degrees nose-up is about right).

• As you know, an ILS is set up so that the glideslope intersects the runway about 1,000 feet from the threshold. For this reason, some instructors teach their students to "duck under" after breaking out of the weather by steepening their descent slightly so as to touchdown closer to the threshold. Please do not do this in this experiment. Instead, try to fly the instrument glideslope all the way to the runway. One technique for doing this is to choose the white fixed distance markers painted 1,000 feet down the runway as your visual aimpoint. Another is to continue to crosscheck the glideslope guidance provided by the symbology even after you have the runway in sight.

• We're not collecting data on the roundout and flare, so don't worry about pulling the power to idle and holding the airplane off for an "on-speed" touchdown.

• On certain trials, there may be a "bent-beam" malfunction of the localizer transmitter. For this reason, you may sometimes notice at breakout that the symbolic runway doesn't quite line up laterally with the real one. If this happens, transition to a visual approach and align yourself with the runway as rapidly as possible, consistent with safe flight. If you feel that you can't make a safe landing for any reason, execute a go-around by adding full power and raising the nose.

• A couple of general points to keep in mind:

Appendix 1 (continued).

- Work hard to maintain airspeed. Although we realize that being one or two knots off of desired approach airspeed is not that critical in a real aircraft, it's important for the purposes of this study that you always strive to be at exactly 90 knots, including during your visual descent after breaking out of the clouds.

- If you get very slow (75 knots or below), a message will appear warning you that you're approaching a stall. Similarly, if you get very fast (115 knots or above), a message will warn you that you're about to overspeed your gear and flaps.

- The simulation includes turbulence, so plan on being bounced around a little. Also, there's no way to trim our simulator and the yoke doesn't stay where you put it, so don't expect to fly "hands off" like you could in a real airplane.

- Again, thanks for taking the time to participate!

Appendix 2. Subject instructions for non-conformal symbology

Subject Instructions
HUD Experiment 94NC

• Thank you for participating in this experiment. We're trying very hard to make sure your contribution to this study will translate into meaningful information for the designers of future cockpit displays. As you may know, Head-Up Displays have found their way into both air carrier (Alaska and Northwest airlines) and corporate aircraft. NASA is very interested in determining the appropriate symbology to be presented both head-up and head-down.

• The experiment will consist of flying multiple ILS approaches in weather conditions near published minimums. On some approaches your instrument symbology will be superimposed on the visual world (head-up) and on others it will be positioned head-down. The symbology set you'll fly with is made up mostly of elements you're already familiar with. Here's a description of the less self-explanatory elements:

- Pitch is represented by a "w" shaped miniature aircraft similar to the one in the center of an attitude indicator. By comparing it to the pitch ladder (markings every 5° above and below the horizon line), you can tell where your nose is pointed. Of course, just because your nose is pointed above the *horizon doesn't mean you're climbing* -- your flight path angle also depends on your angle-of-attack (AOA).

- Your position relative to the localizer course and glideslope is shown by two "crosshairs". The vertical one is a Course Deviation Indicator (CDI), and the horizontal one is a Glide Slope Indicator (GSI). They move in the way you're used to: CDI left of center means that the localizer course is to your left, while GSI above center means that the glideslope is above you.

- The altimeter closest to the center of the display shows radar altitude, which is always AGL.

• After you've gotten the controls in a comfortable position, start the trial by pressing the red button under your left thumb. You will start each trial at 1,000 feet AGL, inside of the glideslope intercept point, configured for landing, and establised in a 3° descent. Power will be set to 75% and airspeed will equal 90 knots, which is your desired approach speed. Please try to maintain exactly 90 knots all the way to the ground. At this speed, it will take about 2 degrees of nose-up pitch to give you a flightpath which is 3 degrees down. There will be no crosswind, so the key to staying on the localizer course is to keep your heading close to the published ILS front course (050, in this case). If you get off course, make a controlled correction of a few degrees to get back on.

Appendix 2 (continued).

• Decision Height on this approach is 200 feet AGL, so when you've descended to within a couple of hundred feet of this altitude you should start bringing the "out-the-window" view into your crosscheck. If you break out of the weather and sight the runway prior to DH, immediately say "runway in sight" and transition to a visual landing. The experimenter will be trying to record the exact moment when you first sight the runway by hitting a key, so please say this phrase promptly and distinctly.

• If you get to 200 feet radar altitude and still don't see the runway, execute a missed approach. As it says in AIM, you should go missed approach if you feel that "1) visual reference to the runway environment is insufficient to land" or 2) you feel that "a safe landing is not possible" (para. 404a). Execute a missed approach or go-around by pushing the throttle to full power while smoothly raising the nose (8 - 10 degrees nose-up is about right).

• As you know, an ILS is set up so that the glideslope intersects the runway about 1,000 feet from the threshold. For this reason, some instructors teach their students to "duck under" after breaking out of the weather by steepening their descent slightly so as to touchdown closer to the threshold. Please do not do this in this experiment. Instead, try to fly the instrument glideslope all the way to the runway. One technique for doing this is to choose the white fixed distance markers painted 1,000 feet down the runway as your visual aimpoint. Another is to continue to crosscheck the glideslope guidance provided by the symbology even after you have the runway in sight.

• We're not collecting data on the roundout and flare, so don't worry about pulling the power to idle and holding the airplane off for an "on-speed" touchdown.

• On certain trials, there may be a "bent-beam" malfunction of the localizer transmitter. For this reason, you may sometimes notice at breakout that the CDI shows right on, but the runway is slightly off to one side. If this happens, transition to a visual approach and align yourself with the runway as rapidly as possible, consistent with safe flight. If you feel that you can't make a safe landing for any reason, execute a go-around by adding full power and raising the nose.

• A couple of general points to keep in mind:

- Work hard to maintain airspeed. Although we realize that being one or two knots off of desired approach airspeed is not that critical in a real aircraft, it's important for the purposes of this study that you always strive to be at exactly 90 knots, including during your visual descent after breaking out of the clouds.

Appendix 2 (continued).

- If you get very slow (75 knots or below), a message will appear warning you that you're approaching a stall. Similarly, if you get very fast (115 knots or above), a message will warn you that you're about to overspeed you gear and flaps.

- The simulation includes turbulence, so plan on being bounced around a little. Also, there's no way to trim our simulator and the yoke doesn't stay where you put it, so don't expect to fly "hands off" like you could in a real airplane.

• Again, thanks for taking the time to participate!

Post-Experiment Questionnaire

Name:

Which symbology location did you prefer? (circle one)

Head-Down Head-Up No Preference

Were you surprised by the runway incursion? Y / N

Did you initiate your go-around as soon as you saw the airliner taxi onto the runway? Y / N

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